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IR absorption diagnostic for carbon chemical erosion in PISCES
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The purpose of this document is to access the cost/feasibility of IR absorption spectroscopy in PISCES-A for the detection of CH_4 and H_3^+ and possibly HeH^+. All of these molecules have an absorption band in the mid-IR around 3.5 µm and weaker absorption bands in the near-IR around 2 µm (100× weaker for CH_4 and 10× weaker for H_3^+). Despite the weaker lines, I would prefer to try to measure the near-IR bands because the hardware is much more straightforward: standard fused silica transmission optics and optical fibers can be used and laser and detector diodes are readily available. In the mid-IR, silica is opaque, so optical fibers don't transmit, reflection optics (off-axis parabloids) are usually used, and lasers and detectors are more expensive.

IR absorption spectroscopy of CH_4 using the $2\nu_3$ band going from 1.62-1.7 µm has been performed successfully for measuring trace quantities of CH_4 in atmospheric-pressure combustion experiments [1,2] and main-species quantities of CH_4 in an inductively-coupled plasmas [3]. In Ref. [3], CH_4 at a density of $n = 10^{12}$ cm^{-3} is detected using a 40-pass Harriott cell. The depth of the absorption peak was about 10^{-4} with this setup; this small peak was picked out of the noise by sweeping the laser frequency and using a lock-in amplifier. These diode lasers can be tuned in frequency either by changing the injection current (which changes the diode temperature) or by directly heating/cooling the diode. Injection tuning has the advantage that the laser can be swept quickly (up to MHz), but the disadvantage that the laser intensity changes and mode-hops are experienced (i.e. the frequency scan isn't smooth). Temperature tuning avoids mode hops and large intensity changes but is slower (< 1 Hz). The width of the scan is of order 0.004 µm for diode lasers at 1.65 µm; this is sufficiently wide to measure three rotational lines in the CH_4 $2\nu_3$ band structure; these can be fit to obtain the rotational temperature, estimate the strength of the entire band, and the estimate the line-integrated density of CH_4.

In PISCES-A, I readily constructed a 16-pass White cell for an uncollimated (tungsten lamp) source, so I do not think making a 40-pass cell with collimated laser light will be difficult. Because transmission optics are readily available at 1.6 µm, however, I would prefer to make a <u>linear optical cavity</u>. With an optical cavity, 100 bounces should be easy to achieve and much more localized measurements (down to the dispersion-limited spot size) can be made.

For <u>chemical erosion measurements</u> in PISCES-A, I assume an erosion yield of Y = 0.05

 [Y= 0.015 for 100eV D^+ at room temperature (Fig. 1 Tawara's chapter in Janev's book (1995)) or 33% of the assumed value of 0.05. The CD_4 production rate is also given in Fig. 1 as ~0.011 CD_4 per incident D^+ ion]

Heating the graphite above room temperature will increase Y and the production rate of CD_4. Y increases with ion momentum transfer. D^+ ions have a larger yield than H^+under otherwise similar conditions. Mixing of D and H isotopes in the main plasma and in the as graphite sample itself would cause chemical erosion production of mixed mass CD_nH_m (where n+m=4). In this case isotope shifts might occur in spectral bands (need more info. on this) which could affect the detection scheme.

Y=, an ion flux of $\Gamma = 10^{18}/cm^2/s$, and room-temperature emitted CH_4. The near-surface density of CH_4 is then expected to be of order $\Gamma Y/v = (10^{18})(0.05)/(4\times10^4) = 1.2\times10^{12}$ cm^{-3}, where v is the thermal velocity of the CH_4 molecule. [This estimate is approximately x5 larger than what I get using the CD_4 production rate in Tarawa Fig. 1]

Measurement of CH_4 densities in this range were achieved in Ref. [3] using laser frequency sweeping and lock-in signal averaging techniques. [The CD4 density may be ~20-30% of the 1.2x1012 cm-3 number, can we still detect it?]

A further consideration for PISCES-A is the breakup of the CH_4 molecule. The expected length scale for breakup is several mm, [CH_4 breakup cross sections are needed]. Thus spatially localized measurements with a localization << Lmfp-breakup are highly desirable. Spatial profiles are needed as well.

The IR absorption technique can also be applied to the detection of molecular ions in the PISCES plasma. In the case of H_3^+, the signal levels should be similar, since the line is about $10\times$ stronger, but the density is about $10\times$ lower (about 10^{11} cm^{-3}) in typical PISCES A cases.

I would propose measuring CH_4 first. CD_4 has the great advantage of being a neutral gas, hence the measurement technique can be perfected on a CD_4 gas test cell at higher pressures with large signal levels.

Cost Estimate for Diagnostic Development on PISCES-A

Hardware costs for attempting an initial near-IR absorption spectroscopy measurement on PSICES are expected to be of order $10k. I have obtained quotes for several 1.65 μm laser diodes: these range from $2.5k for a bare laser diode (Specdilas D-1650, Laser Components) to $11.8 k for a single wavelength system IR laser system including thermo-electric temperature regulator, intensity regulation, frequency sweep control electronics, and fiber output coupler (DFB 1665-003, Sacher Laser).

Separate lasers are needed for each molecule of interest. We expect to use three different absorption lines for CD4, C2D6, and CD. Cost of lasers 7.5k

The absorption signal to noise ratio can be substantially increased by using signal averaging and phase sensitive detection. The use of a lock in amplifier is essential for

generating good quality data with low signal to noise ratio. Lock in amplifier and associated electronics for signal detection estimated 25k.

The bare-components approach would be cheaper hardware-wise (typical component costs for fiber output coupler, Peltier cooler, etc. are of order several $100 each), but would take more time for setting up, ordering parts, etc. I would recommend trying to purchase a more complete laser, since it will already take me time to set up the optical cavity. Component costs for the optical cavity and detector should be of order $1k or less, since normal silica optics can be used.
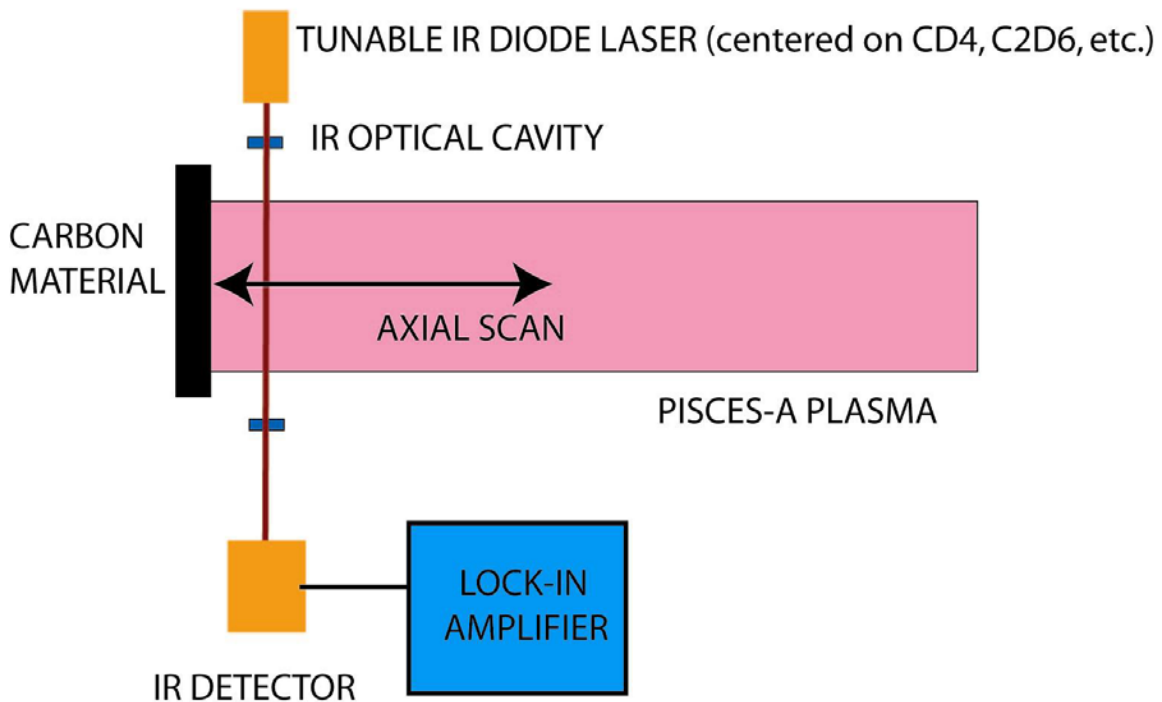
TOTAL FUNDS REQUESTED   35k

REFERENCES
[1] K. Uehara and H. Tai, Applied Optics 31, 809 (1992).
[2] Y. Shimose, T. Okamoto, A. Maruyama, et al., IEEE Phot. Tech. Lett. 3, 86 (1991).
[3] I. Moeller, "Studies on the electron energy distribution in CH_4/O_2 plasmas by means of tunable laser spectroscopy and a simple chemical model," PhD thesis, University of Bochum, 2003.

[4] H. Tarawa in R.K. Janev Atomic and Molecular Processes in Fusion Edge Plasmas, Plenum Press, New York, (1995).

FIGURES

Diagnostic for hydrocarbon species generated by chemical erosion
Each CnDm species has characteristic IR-absorption spectrum,
IR absroption gives line average density of molecule, axial scan follows
breakup.

TUNABLE IR DIODE LASER (centered on CD4, C2D6, etc.)

IR OPTICAL CAVITY

CARBON MATERIAL

AXIAL SCAN

PISCES-A PLASMA

LOCK-IN AMPLIFIER

IR DETECTOR

UCSD PISCES-A   CONFIGURED AS GASEOUS DIVERTOR SIMULATOR (SCHEMATIC)

HOT ELECTRONS
CAUSE
VOLUMETRIC
IONIZATION
OF INLET GAS

PLASMA PLUGGING
PREVENTS HIGH PRESSURE
IN GAS TARGET FROM REACHING
LOW PRESSURE PLASMA SOURCE

GAS TARGET
PLASMA DETACHMENT
REGION
LARGE PARALLEL
GRADIENTS

SOLID STATE
MATERIAL TARGET

PLASMA
SOURCE
P ~ 2.5 mTorr

PLASMA PLUGGED
GAS BAFFLE TUBE
(DIVERTOR THROAT)

GAS TARGET
INTERACTION
REGION
P ~ 30 mTorr